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Drop Size: Drift and Effectiveness of Herbicide Sprays

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DROP SIZE: DRIFT AND EFFECTIVENESS OF HERBICIDE SPRAYS

by

John W. Barry[1]

In the application of herbicide sprays we strive for uniform coverage of the target area. To achieve this coverage the herbicide drops must be in a relatively narrow range of drop sizes. If the drops are too small they may remain airborne and drift off target; if the drops are too large they may not provide adequate coverage. The elements discussed in this paper relate to the drop size of herbicide spray and its relationship to efficiency and drift. Delivering the proper number and size of herbicide drops to the target is a challenging task. All events from planning, equipment selection, and weather conditions existing during application, affect the drop size spectrum. Project officers should be familiar with the interrelationship of these events and parameters. Safe and effective use of herbicides is centered around the selection of the drop size range.

Spray systems developed to date, including the Microfoil[R] system and the Raindrop[R] nozzle, generate driftable drops. We have the capability to eliminate significant drift; but drift, per se, cannot be eliminated. How many of us know how to minimize drift? Are we familiar with drift control methods? Do we know how to use these methods? Is drift always bad? Efficient herbicide application is mandated by the high cost of herbicides and application, and by cost, in terms of dollars and manpower, of activities related to off-target drift. Inefficiency is pricing itself out of the market.

Drop Size

Why so much concern about drop size? Drop size holds the key to reducing drift and to producing effective coverage. Ekblad and Barry (1983) reviewed the drop size problem, graphically illustrating the relationship of wind, swath displacement, drop density, turbulence, target size, etc., to drop size. By applying a narrow drop spectrum it is possible to reduce the number of driftable fine drops and to reduce wastefulness of large drops. Fine drops, generally those <100 µm, are subject to drift (Yates and Akesson 1973), while most of the larger droplets (>100 µm), if properly applied, deposit in the treatment block. The larger drops represent a relatively small number of the total drops and a large percentage of the tank mix volume, as illustrated in Table 1. The effectiveness of the largest drops in the spectrum i.e., >500 µm, is minor—as they come in contact with but a small fraction of the treatment area (Newton 1984a).

Traditionally, to control drift the emphasis has been to use large drops. We must weigh the trade-off, that being, effective coverage of the target vegetation with an adequate number of drops accompanied with drift vs poor coverage with an inadequate number of drops but still with some drift. If drift were not a problem it would be best to select a small drop size range

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In the application of [illegible] the [illegible] target area. In addition [illegible] relatively narrow range of [illegible] enough diffusion and drift [illegible] provide adequate coverage. The [illegible] drop sizes of pesticide sprays and the relationship [illegible] protecting the [illegible] engineering team. [illegible] conditions, including [illegible] and herbicides, [illegible] and [illegible]. Safe and effective use of [illegible] selection of the drop size range.

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Drop Size

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and possibly lower application volumes, that is, use the same amount of active ingredient but with less water. Applied when the surface is cool, even under moderate winds, small drops can be highly effective with minimal drift. When application expertise, however, is lacking on the part of the applicator and the project leader, one should take a more conservative approach and lean toward the larger drop spectrum.

Specific factors known to influence drop size include nozzle type, nozzle orifice size (flowrate), nozzle orientation relative to airstream, lateral position of nozzle on the boom, forward speed of the spray system, boom pressure, and chemical and physical properties of the tank mix. In other words, drop size is related to flowrate, pressure, fluid behavior, and shear at the nozzle orifice.

A major concern has been the range of drop sizes produced by the various nozzle types. The range varies considerably among nozzle types according to how the nozzle is used. Nevertheless, even the best nozzle produces a wide drop size range--definitely a range wider than desired. With the use of lasers (Yates 1983b) in recent years we have become acutely aware that all nozzles produce a large number of small, driftable drops. Of course some nozzles produce more than others.

Table 1. Relationship of drop size to coverage using 1 gallon of liquid uniformly applied to an acre in a mono-disperse spray. (Adapted from Potts 1958).

Drop diameter (μm)	No. of drops per cm^2	Mean distance apart in cm
10	213,500	0.00216
20	26,700	0.00615
30	7,910	0.0112
40	3,335	0.0173
50	1,708	0.0242
75	560	0.0425
100	213.5	0.0685
150	63.2	0.126
200	26.7	0.193
300	7.91	0.356
400	3.33	0.551
500	1.71	0.708
750	0.56	1.34
1000	0.213	2.16

For most herbicide applications we strive for a high density of herbicide drops on the target foliage i.e., 20 drops/cm^2 (Newton 1984). To reemphasize, we attempt to achieve this by reducing the number of small drops that drift or volatilize, and the number of large drops that provide poor coverage.

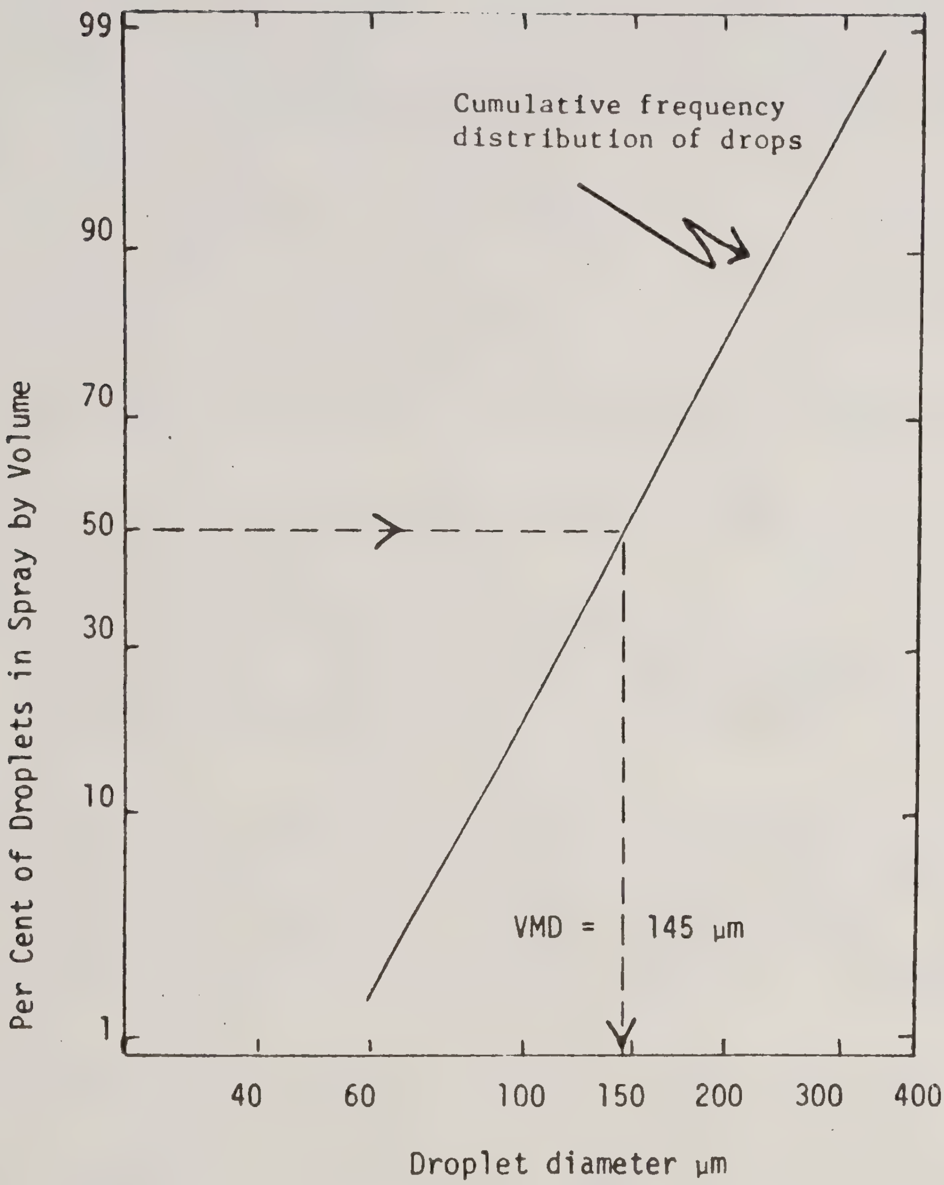

Figure 1. Illustration of volume median diameter (VMD).

Drop size spectrum of a spray cloud or for a specific nozzle is expressed as the volume median diameter (VMD). Also expressed as $D_{vo.5}$, the VMD is the diameter which divides the spray drop spectrum in two equal parts by volume. Thus, 50% of the volume is atomized in drops with diameters less than the VMD and 50% of the volume is in drops with diameters greater than the VMD. Figure 1 illustrates how the VMD is determined.

Drop size is a "catch 22" problem because:

- Small drops drift
- Small drops evaporate and disappear
- Small drops increase coverage
- Small drops penetrate canopies
- Small drops deposit on both sides of leaves
- Small drops in high volume sprays contain small percentages of the tank mix

- Large drops deposit on treatment block
- Large drops are less volatile
- Large drops give poor coverage
- Large drops do not penetrate canopies
- Large drops do not deposit on underside of foliage
- Large drops from high volume sprays contain a large percentage of the tank mix volume
- Large drops may burn non-targeted foliage

For any particular situation, and taking into consideration target and nontarget species, meteorology, topography, sensitive areas, application method and tank mix, there is an ideal drop size range. We do not know this range precisely for all situations. Consequently we prescribe a large application rate (>10 gpa), and a nozzle that will give the narrowest drop spectrum possible. This is the best we can do presently, in practice; we can do much better, in theory.

Although there are many knowledge gaps it is my opinion that most silviculturists and applicators are not using existing knowledge. Are the spray application procedures reported by Gratkowski and Stewart (1973); Gratkowski (1974); Stewart and Gratkowski (1976) and Newton (1984 and 1984a) being followed by most of us? I would guess not.

Aircraft Calibration

Calibration is simply a method of determining and measuring the flowrate. It is important that project officers understand how spray systems are calibrated. Unfortunately we cannot rely upon the applicator to arrive on-site with a properly functioning, clean, and calibrated spray system. Reichenberger (1980), in an article entitled The Billion-Dollar Blunder, pointed out the severity of the calibration problem. Reichenberger states that "Two of every three pesticide applicators were making significant application errors--the result of inaccurate calibration, incorrect mixing, worn equipment and failure to read the product label." It has been my experience with aerial application that applicators seldom arrive on site with properly calibrated equipment. Problems which are commonly encountered when the application equipment arrives on site include:

- Calibration - flowrate not within specifications
- Dirty system - strainers and screens dirty and sometimes missing, debris in tank and booms
- Nozzles - wrong size, mixed sizes, worn, and dripping due to dirty or fatigued check valves and diaphragms
- Pressure gauge - inoperative or defective
- Nozzle orientation - wrong orientation for desired drop size
- Nozzle placement - nozzles on ends of boom within the effects of rotor tip vortices or not placed optimally to provide even swath

During the course of calibration these problems can be identified and corrected if you have a cooperative applicator, necessary equipment, tools, and nozzles. Applying the proper amounts of herbicide in the desired drop size spectrum, evenly across the treatment block, depends upon proper calibration.

Aircraft Calibration (calculating number of nozzles)

As the aircraft sprays, it must, for its planned speed, swath width, and desired application rate, disperse spray at a given volume per minute. This is called the flowrate.

1. Flowrate can be calculated easily by the following equation:

$$\text{Flowrate in gallons per minute} = \frac{\underset{\text{(ft)}}{\text{swath width}} \times \underset{\text{(mph)}}{\text{airspeed}} \times \underset{\text{(gal/acre)}}{\text{application rate}}}{495}$$

The silviculturist decides on the application rate per acre while the applicator provides inputs on swath width and airspeed. Given a 50 mph air speed, a 75 foot swath width and a 10 gallon per acre application rate we calculate the flowrate in gallons per minute to be:

$$\text{Flowrate} = \frac{\text{75 ft X 50 mph X 10 gpa}}{495}$$

$$\text{Flowrate} = \text{76 gallons per minute}$$

Now we know how much spray should be applied each minute the applicator is spraying over the treatment block to achieve the 10 gpa prescribed by the silviculturist.

2. The next step is to select a nozzle. Let's select the D8-46. The nozzle may have been recommended by a forest extension agent or a silviculturist experienced in aerial application. The Spraying Systems Co. technical data sheet #4498 (Anonymous 1960) shows a flowrate of 1.59 gallons per minute at 30 psi for the D8-46 nozzle. A pressure of 30 psi is commonly used for herbicides. To determine the number of nozzles divide 1.59 (flowrate for a single nozzle) into 76 (flowrate for the entire spray system). The answer is 48. The spray boom, therefore, should be fitted with 48 of the D8-46 nozzles as calculated below:

$$\text{Number of nozzles} = \frac{\text{Flowrate from Step 1}}{\text{Flowrate for single nozzle from data sheet}}$$

$$\text{Number of nozzles} = \frac{76}{1.59} = 48$$

Aircraft Calibration (checking flowrate)

After installing the nozzles the system's flowrate and effective swath width should be checked. This is usually done with water after the spray system has been cleaned and the proper size and number of nozzles are installed. The three most common calibration methods are:

1. Collecting spray from nozzles. The helicopter sprays while sitting on the ground. Tubing is used to collect the water spray from at least 2 nozzles on each boom. If the helicopter sprays for 1 minute the total spray collected from the 4 nozzles should equal 6.36 gallons. This figure was obtained by multiplying flowrate single nozzle 1.59 X 4 nozzles X 1 minute.

2. Checking level in spray tank. Mark the level of water in the tanks and have the helicopter spray for 1 minute, on the ground or airborne. Again check and mark the level in the tanks. Then measure the number of gallons required to refill the tanks to the original marked level. It should take 76 gallons.

3. Pressure drop. The system is filled with about 30 gallons of water and the helicopter sprays until boom pressure is lost. This will be noticed as a sharp drop in pressure from the 30 pounds per square inch shown on the pressure gauge. The spray system is shut off and the system is now primed; that is, fluid is in the boom and nozzles. The prime is the residual fluid which usually remains in the spray system after the pressure drop. Then fill the system with 76 gallons of water. It should take 1 minute to disperse the 76 gallons before the pressure drops.

The preferred method of increasing or decreasing the flowrate is by adding or subtracting nozzles. Because nozzle size and boom pressure affect drop size, it is preferable to maintain the same nozzle size and boom pressure. Unfortunately it is common practice for applicators to use the pressure regulating valve to increase or decrease flowrate and thence application rate. Increasing boom pressure also will decrease drop size.

You may have to make several attempts before the system is calibrated. If the flowrate is consistently high or low then simply reduce or add nozzles. If the flowrate is inconsistent, the flow may be restricted by clogging, dirty line strainer, variable boom pressure due to pump failure or erratic pressure relief valve on the by-pass line.

Adjuvants

Adjuvants are added to tank mixes to influence properties of the tank mix. These may be used specifically to aid in sticking and spreading spray drops on foliage, to protect the active ingredient from UV radiation, to reduce drop evaporation, to provide rainfastness, etc. For herbicide tank mixes adjuvants are used to aid in spreading the drop on leaf surfaces and to increase drop size. The reduce-drift-type polymer adjuvants i.e., Nalco-Trol[R], Lo-Drift[R], and Orthotrol[R] are water soluble. In theory they reduce the number of fine drops during atomization. Akesson and Yates (1981) reported, "The elasticity effect is very sensitive to formulations, particularly the addition of soluble salts such as many of the herbicides may contain. The addition of a polymer will not always provide drop size control and so it should not be recommended for all uses. Where high shear rates are imposed on the spray, such as from an aircraft producing small spray drops or with high pressure ground machines, the polymer is broken down and effectiveness is limited or lost. The material must be checked with each formulation and rate of dilution to determine proper and effective amounts of polymer to use." Gratkowski and Stewart (1973) and Gratkowski (1974) discuss other adjuvants and their application.

Haq (1981) studied the relationship of fluid physics to drop size distribution from nozzles used in agriculture. He found that drop size is increased by increases in flowrate, surface tension, and viscoelasticity. Viscosity showed little effect on drop size and flowrate. For jet nozzles flowrate is the single most important factor affecting drop size--as the flowrate increases the drop size increases. Viscoelasticity had a greater influence on increasing drop size of the hollow cone nozzle than for other nozzles tested.

In another study (Yates et al. 1976) the number of drops below 200 µm was reduced by adding adjuvants. One was hydroxyethyl cellulose buffer and the other Nalco-Trol. When these adjuvants were used with a low shear nozzle directed straight back (0°, Figure 2), 0.75 percent or less of the spray volume consisted of drops below 200 µm. Without the adjuvants 4 percent or more of the spray volume consisted of drops below 200 µm.

More information is needed on the affects of adjuvants on herbicide tank mixes. It is possible that with some adjuvants we are making a few large drops and sacrificing coverage and not reducing, significantly, the driftable drops. This observation still must be tested by controlled experiments in wind tunnels and in the field. An adjuvant is no help at all if it means poor control, higher application rates, and more herbicide with no decrease in real risk of drift damage.

Aircraft Spray Systems

Small helicopters are commonly used to apply herbicides to western forests. They are maneuverable over complex terrain and can operate from helispots near treatment areas. The Hiller 12E helicopter, with or without Soloy turbine conversions, and the Hughes 500 helicopter are the work horses. They fly from 45 to 70 mph depending upon payload, temperature, elevation, topography, and engine type.

[illegible]

[illegible] (1981) [illegible]

[illegible] only showed [illegible] where is one [illegible] also increased [illegible] lowest on increasing [illegible] at a break.

[illegible] et al. 1970 [illegible] Figure 7), 0.73 per [illegible] correlated at depths below 2.0 cm. [illegible]

[illegible] is needed in the study of [illegible]

[illegible]

Spray helicopters are usually equipped with a boom and nozzle system. The Microfoil system also is used by a few applicators for special situations such as spraying rights-of-way. Spray systems consist of a tank, pump, and nozzles. The nozzles frequently used are the D8 jet and the D8-46 hollow cone produced by Spraying Systems Co. and Delavan Corp. Presently the D8-46 is the most commonly used nozzle for applying herbicides in forestry; however, local regulations may require the D8 jet nozzles--no core. Testing by Yates et al. (1983) University of California, Davis, (UCD) has shown the D8-46 currently to be the nozzle of choice for 10 gpa work with growth regulator-type herbicides. It produces a 500 μm VMD when oriented straight back at airspeeds of 50 mph. The drop size range is narrow with relatively few fine drops. Other nozzles, such as the D8 jet oriented straight back, produce VMD's of around 900 μm. When the D8 is oriented down it produces more fine drops than the D8-46 similarly oriented. The D8 droplet size spectrum, under most situations, is broad. To reemphasize, in spraying herbicides we wish to reduce the fine drops that drift and the large drops that reduce coverage. For most forestry operations the D8 does not meet this requirement.

Another nozzle that has gained popularity is the Raindrop®. It has not been demonstrated scientifically to be superior to the D8-46 nozzle in terms of drift reduction. Considerably more testing will be required before the Raindrop nozzle can be recommended as a drift reduction nozzle.

Engineers have attempted to design nozzles with a narrow spectrum. The spinning disk (Herbi®) for ground application of herbicide and the rotary Beecomist® for aerial application of insecticides are examples of atomizers that produce a narrower drop spectrum than conventional hydraulic pressure nozzles. The advantages of spinning disk and rotary type atomizers can be negated easily if they are not used in accordance with manufacturer's instructions.

A test series sponsored by the USDA Forest Service (FS) is scheduled at the UCD wind tunnel with a completion date of October 1984. Using the PMS laser system, atomization data will be collected on the hollow cone, jet and Raindrop nozzles. Until these tests are completed the recommendation to achieve a 500 μm VMD is the D8-46 directed backwards. For smaller VMD's the nozzle should be oriented between 0° and 45° for slight reduction and between 90° - 135° for fine atomization. Always avoid 180° orientation (Figure 2).

The Microfoil boom is used for special situations. Of the currently available liquid spray systems, the Microfoil is the best choice for reducing drift, providing the helicopter flies <60 mph. The system produces a narrow drop spectrum with a VMD around 900 μm. Because the drops are large and there is little lateral spreading of the spray cloud, the application rate should be increased to 30-40 gpa (Newton 1984a). The narrow swath width also necessitates accurate flying to prevent skips.

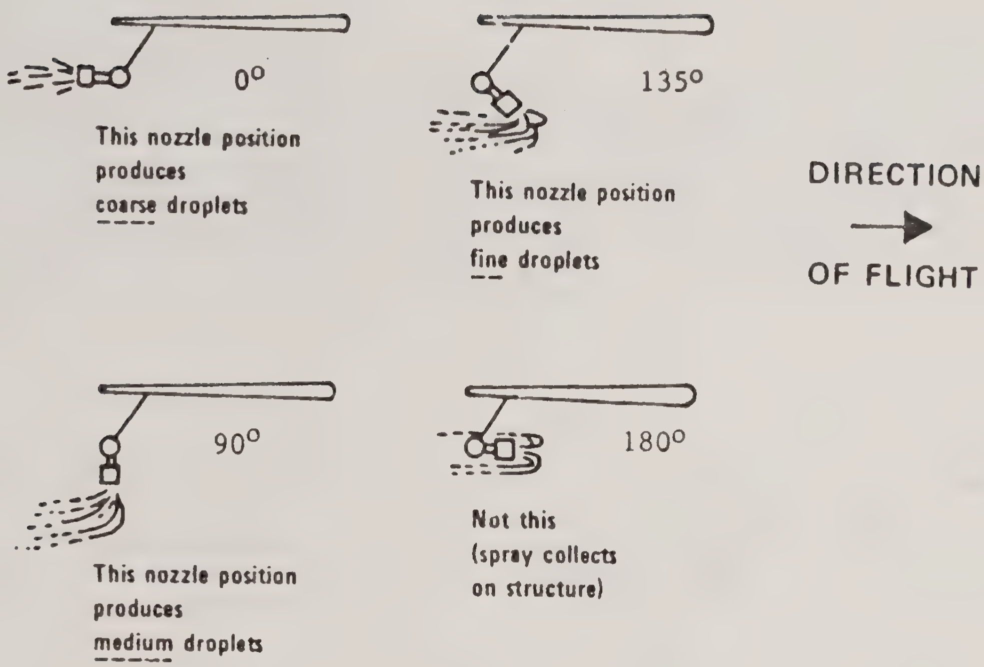

Figure 2. The angle of the nozzle in relation to the direction of travel affects droplet size.

Spray Deposit Assessment

The most common method of monitoring herbicide spray deposits is with paper (Barry et al. 1978). Most white papers will work if the spray is dyed. Special papers, however, are required for undyed sprays. They provide data on number of drops per unit area and relative or absolute drop size. Kautz and Ekblad (in press) have prepared a publication which illustrates, in color, deposit papers for sampling undyed sprays. Their publication, which will be available in 1984, can be obtained from the Forest Service, either the Missoula Equipment Development Center, Missoula, MT 59807 or Forest Pest Management, 2810 Chiles Rd., Davis, CA 95616. Papers suitable for detecting herbicide sprays include:

1. White Kromekote[R] - recommended for dyed spray

2. Ciba-Geigy oil sensitive - will detect some undyed oil sprays

3. Ciba-Geigy water sensitive - will detect sprays containing water

4. Kodak 580 paper - will detect some undyed sprays

5. Thermofax[R] 209 copy, type 658 copy paper - will detect some undyed sprays

Before selecting a deposit paper you should test the paper by spraying a test batch of the herbicide tank mix.

Spray deposit papers are useful to determine:

1. Quality of the application - coverage (drop deposit density), and uniformity of the deposit and drop size. Note that to determine drop size you will need to know how much the drop spreads on the paper. Spread factors for some tank mixes are listed by Barry et al. (1978). For spread factors of other tank mixes contact Wes Yates, Dept. Agricultural Engineering, University of California, Davis, CA (916) 752-0474.

2. Deposit in buffer and other non-target areas.

3. Applicator conformance to contract terms.

In addition, deposit sampling demonstrates that we are concerned about potential drift, it provides data for improving future applications, and it provides a record in the event there is an accusation that the herbicide was deposited beyond the treatment block. We have observed also that applicators do a better job when the spray is monitored with deposit papers.

Sources for these papers are listed in the handout "Sources of Material for Spray Deposit Assessment," (Anonymous 1984).

Checking Aircraft Spray Pattern

Referred to as aircraft characterization, the procedure involves the aircraft spraying over deposit cards. This is done to check swath width, drop size, drop density, and to look for drips and other malfunctions in the spray system. For those interested a procedure is discussed in detail by Dumbauld and Rafferty (1977). It is worthwhile to note that deposit patterns are variable with changes in nozzles, positioning of nozzles on the boom, release height above the target, tank mixes and airspeed. Allowing for these, one will find deposits are still innately variable. So it is unwise to go into lengthy spray characterization procedures of this kind on a "do it yourself" basis. If you have need for a thorough characterization it is best to consult a specialist. For most herbicide applications a simple check of the spray pattern will be adequate. Set up a 200-foot line of deposit papers spaced 10 feet apart. Have the pilot fly into the wind and perpendicular to the line. This procedure will provide information on swath width, drop deposit density and evenness of the swath. It is recommended that you make at least 3 spray runs over the line, replacing samplers after each run.

Aerial Spray Contract

The contract should specify the tank mix, drop size, drop density, application rate, spray release height, allowable meteorological conditions, location of buffer zones, and provisions for calibration. The contract should mention how acceptable spray coverage will be determined, and by whom. You also might want to specify nozzle type and size, nozzle orientation, and boom pressure needed to produce the desired VMD. The project officer, via the contract, should tell the applicator what is needed, otherwise you will likely get an application based upon a non-foresters assessment of the situation.

Regardless of the type of contract, it is essential that the project officer and pilot meet and view the work site either on the ground or from the air. This is the single most important factor for a quality job. You should clearly define the block boundaries, sensitive areas and buffer zones. The pilot should advise on how he plans to spray the block. This dialogue will lead to an understanding of each other's needs. This is a sound step toward eliminating potential problems. A successful project is one in which the target vegetation is controlled and drift to sensitive sites minimized, within reasonable limits.

Meteorology

This is a complex subject. Let's limit our discussion to wind, temperature, and relative humidity.

1. Wind. Light to near calm winds are unpredictable. It is best to have an organized wind flow which carries the spray from sensitive areas. All sprays have driftable components; therefore, it is best that an organized and predictable wind be used to carry the driftable drops from sensitive areas. Light and variable winds, common to early morning, can shift without warning and carry spray into sensitive areas.

2. Temperature. As the morning sun heats the ground, air near the surface is heated and begins to rise. Small drops rise with the heated air. Small spray drops are more likely to settle on target if the ground is cool. Therefore, we recommend that spraying cease when the temperature reaches 75°F. This temperature is somewhat arbitrary. It has proven to be a reasonable spray cut-off temperature when applying pesticides in the West. In springtime, one should usually avoid spraying of herbicides during stable, inversion, or very unstable conditions (Figure 3).

3. Relative Humidity. RH affects evaporation. Water drops can evaporate rapidly in low RH's. Drops below 100 μm in diameter vaporize within seconds. Spraying should be done when RH is over 50%.

Drift Management

During application of pesticides, whether by ground or by air, a small portion of the spray will deposit beyond the treatment block. This loss is commonly referred to as drift. Lateral movement of spray within blocks also has been called drift.

To most people spray drift has negative connotations. And perhaps we tend to over react in our efforts to reduce drift. Drift fills the voids or gaps which often are left between spray swaths. Drift on the downwind side of the treatment block demonstrates that the spray did in fact travel the opposite direction from the sensitive area located upwind. Wind also has been thought of negatively. Certainly wind provides the energy to move spray clouds. But wind also can carry the spray cloud from sensitive areas. It also provides energy to impact spray drops on target foliage—thus assisting spray effectiveness. Wind helps to disperse and evaporate the fine drops harmlessly in the atmosphere.

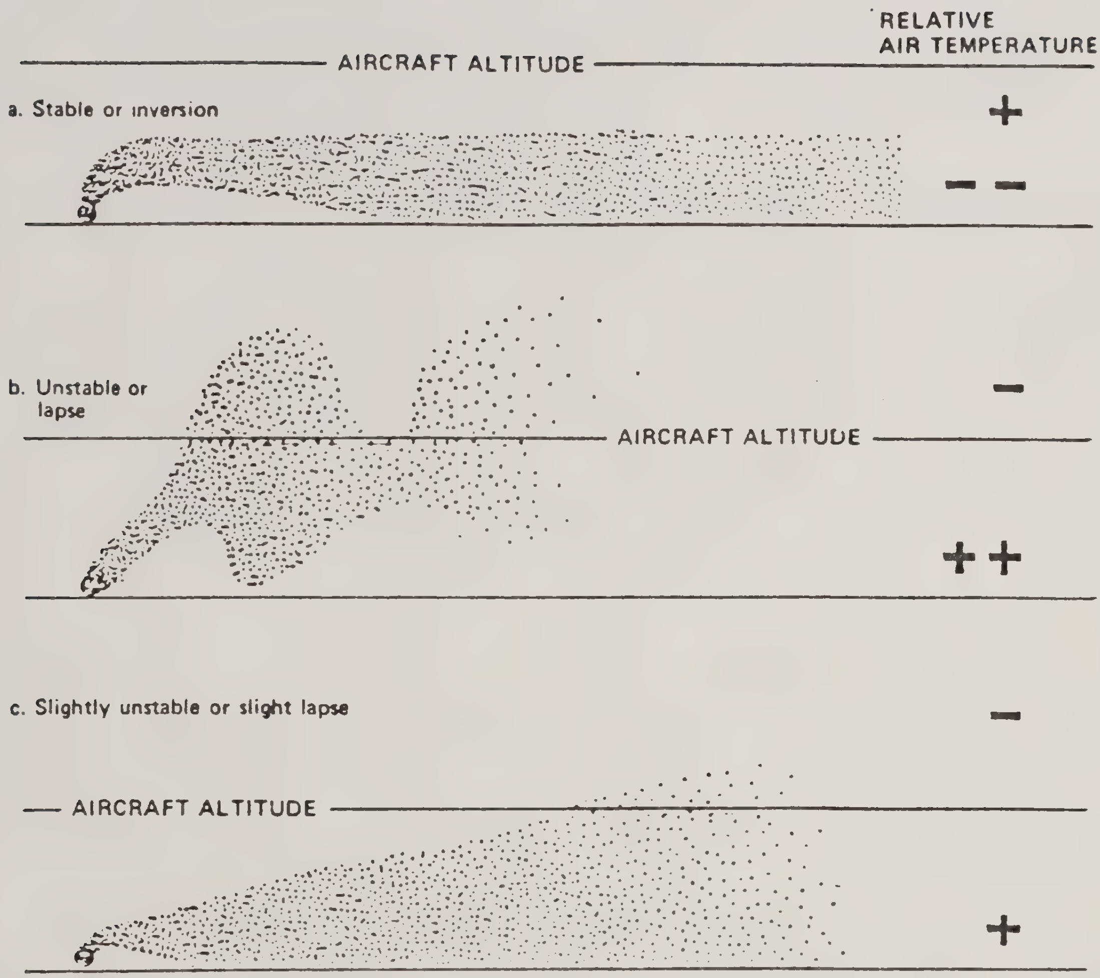

Figure 3. Schematic diagram showing smoke plume diffusion under (a) stable, inversion or calm condition, (b) unstable condition or lapse, and (c) slight lapse, or slightly unstable (Anonymous 1983).

(plus=warmer air, minus=cooler air)

If there are sensitive areas near the treatment block I would discourage spraying under calm conditions. It is best to delay treatment until there is an organized wind flow. Even under calm conditions there is movement and little air mixing. Fine herbicide drops, suspended in the air after treatment, can drift in a concentrated cloud. The fine drops will fall out as the cloud drifts and meanders. When the sun warms the air the cloud will dissipate rapidly. Understanding atmospheric processes will aid you in manipulating drift to your advantage.

Drift management is the responsibility of both the project officer and the applicator. If a drift problem develops, both are involved. Managing drift should begin during the project planning phase. Dealing with drift problems is time consuming and the consequences of drift can be nearly overwhelming, but one must maintain his or her perspective. Spray drifts with the wind, and the only observable consequence of herbicide drift is damage to sensitive plants. Such damage is normally of concern only when it occurs as a trespass on neighboring lands. Drift onto one's own land is not normally a problem, and may actually be evidence that spraying was being done under wind conditions favorable to the neighbor. It is unwise to attempt to prevent all drift--in doing so, one will inevitably lose efficacy and respraying may be required.

Minimizing Drift

1. Project planning. Proper prior planning prevents poor performance. Technical planning includes selecting type of aircraft, tank mix (herbicide, carriers, adjuvants, dyes) and drop size; defining and marking treatment boundaries; identifying acceptable meteorological conditions; providing for buffer strips; and communicating with the applicator.

2. Equipment checking. Checking equipment can reduce such problems as dripping nozzles. If the aircraft drips herbicide on neighboring properties, especially automobiles, you have a problem. Spray equipment should be clean and calibrated. Unfortunately it cannot be assumed that the spray equipment will arrive on site clean, calibrated, and ready to spray. If it is clean on arrival, keep an eye on it during the project and watch for leaking nozzles.

3. Monitoring. Spray deposits should be monitored downwind of the treatment block. The wind direction can be monitored with smoke. It is good practice to use smoke before and during spray projects. You can make on site decisions regarding spray swath beginning and ending points.

Specifics of drift control have been reviewed by numerous specialists i.e., Gratkowski (1974), Yates (1984), and Warren (1976).

Basically drift control of herbicides involves reducing the number of drops below 100 m in diameter and by restricting their movement. Also increasing the VMD decreases the number of driftable drops. Table 2 illustrates the relationship of VMD to the number of driftable drops. For a 501 VMD the percent drops in the driftable range (<123 μm) was 1.16% compared to 3.40% for a 271 VMD, and 12.93% for a 189 VMD. Note also the increase in the number of effective drops, those between 154 and 284 μm, as the VMD decreases.

[illegible] ... Unfortunately [illegible] ... calibrated, [illegible]

[illegible] Spray deposits should [illegible]

[illegible] block. The wind direction [illegible]

Table 2. Atomization of water drops in the 56 to 578 μm range using D8-46 nozzle, 40 psi. Data from Yates et al. (1983).

Drop Size Category (μm) (upper limit)	Number Drop/Sec. for VMD 189[1] (μm)	271[2] (μm)	501[3] (μm)	Percent Volume for VMD 189 (μm)	271 (μm)	501 (μm)
56	2.01E7	5.84E6	7.11E6	1.83	0.27	0.21
89	7.29E6	3.68E6	2.28E6	4.03	1.02	0.40
122	4.13E6	2.49E6	1.05E6	6.97	2.11	0.56
154	4.53E6	3.52E6	1.07E6	17.22	6.73	1.29
187	2.61E6	2.75E6	948596	18.81	9.96	2.17
219	1.32E6	1.99E6	717337	16.10	12.14	2.77
252	786186	1.07E6	550981	14.89	10.22	3.32
284	527169	940013	415550	14.72	13.19	3.69
318	52317	474428	346889	2.09	9.52	4.41
351	10633	196110	268303	0.58	5.36	4.64
382	18152	159382	250602	1.29	5.68	5.66
414	4160	106009	164700	0.38	4.87	4.80
447	1925	69816	153751	0.22	4.06	5.67
479	3624	80362	147612	0.52	5.82	6.77
512	2044	15523	96196	0.36	1.38	5.41
545	0	4270	79528	0	0.46	5.42
578	0	1949	52871	0	0.25	4.32

1. Nozzle directed 90°; 150 mph
2. Nozzle oriented 0°; 150 mph
3. Nozzle oriented 0°; 50 mph

Table 2 also illustrates the influence of nozzle orientation and airspeed on VMD. The large 501 VMD was produced with the D8-46 nozzle oriented straight back (0°) in an airstream of 50 mph, while the small 189 VMD was produced with the nozzle straight down (90°) in an airstream of 150 mph.

The type of tank mix - oil, water base or invert emulsion will dictate field procedures for controlling drift and maximizing deposit in the treatment block. In deciding on the appropriate drop size range one must consider the target and the chemical's mode of action. Soil active herbicides, such as atrazine and velpar, can be applied in large drops with no loss of effectiveness[1]. As shown in Table 3 other herbicides should be applied in small drops to cover the leaf as the mode of action starts at the leaf surface.

1. Personal communication with Mike Newton, Dept. of Forestry Sciences, Oregon State University.

Table 3. Recommended herbicide application parameters for the Northwest using a helicopter at 50 mph, and boom pressure of 30 psi.[1]

Herbicide	Primary use in Northwest	Drops/cm[2] on leaf	Drop size VMD (μm)	Nozzle[2] size	Orientation degrees[3]	Remarks
Amitrole	Release & site prep, salmonberry	10-20	500-600	D8-46	0^{o}	Surfactant for site prep, 1/2 pt/acre. None for release, esp. on noble fir
Asulam	Bracken fern only	"	"	"	"	
Atrazine	Grass, forbs	"	500-1000	D8 D8-46	45^{o} 0^{o}	None needed
Dalapon & Pronamide	Grass only	"	"	"	"	Dalapon best with atrazine (injurious alone)
Dicamba	Not used much-site prep	20+	400-500	D8-46 D6-46	0^{o} 0^{o}	Surfactant; 2,4-D
Fosamine Ammonium	Salmonberry (Riparian)	10-20	500+	D8 D8-46	45^{o} 0^{o}	None
Glyphosate	All deciduous	"	"	"	"	Add surfactant for site prep. 1 pt/ac
Hexazinone	Herbs; brush	20+	400-500	D8-46	0^{o}	
Phenoxys (2,4-D)	broadleaf herbs woody/species	20+	"	D8-46 D6-46	0^{o} 0^{o}	
Picloram	"	"	"	"	"	Surfactant, 1/2 pt/ac
Simazine	Annual grass, forbs	10+	>500	D8 or smaller	0^{o} to 45^{o}	None
Triclopyr	Brush, site prep for pine release, other species	See phenoxys for application data.				

1. Information provided by Mike Newton, Oregon State University, Wes Yates, University of California, Davis, for herbicide application in the Northwest. This information is preliminary. Considerably more research is needed on effective drop size and effectiveness of adjuvants.
2. Spraying Systems Co. "D" series hollow cone nozzle.
3. Nozzles oriented straight back 0^{o}, straight down 90^{o}, and straight forward 0^{o} relative to flight direction.

Oil base, and to some extent invert emulsions, are not affected by low relative humidities. These tank mixes can be applied in the drop size range which is optimum for the target vegetation. Don't be tempted to select a large drop size range for all situations. It might work or you might be out there respraying. Use available information and seek competent advice to decide on the optimum drop size range for your project.

The number of small drops can be reduced by:

- Using larger orifice nozzles
- Using lower boom pressure
- Orienting nozzle such that shear across nozzle orifice is reduced. The drop size decreases as the nozzle is rotated forward (Yates and Akesson 1983).
- Spraying under higher relative humidities helps to reduce evaporation of large water drops into driftable small drops

Movement of spray drops can be restricted by:

- Spraying close to the target (Rafferty 1984)
- Increasing the drop size. Fine water drops will drift and evaporate leaving fine crystalline materials to be widely distributed. Fine oil drops can drift and deposit off-target, but they do not evaporate like water.
- Limiting nozzles to 3/4 of the spray boom
- Spraying water base sprays with temperatures <75° and humidities >50% (Gratkowski 1975)
- Spraying under organized and low wind speeds, and favorable direction (away from sensitive areas)
- Using tank mixes with high specific gravities and using, selectively, adjuvants. Sprays from the heavier tank mixes settle faster than spray from tank mixes that are lighter than water.

Modeling Spray Behavior

The FS has developed a model (Dumbauld et al. 1980), referred to as the Forest Service Cramer/Barry/Grim (FSCBG), which predicts amount of spray that drifts from a treatment block. Given your situation - aircraft type, spray system, release height, drop size spectrum, meteorological conditions (those anticipated during treatment), and tank mix - the model will predict deposit in the treatment block and drift for that set of conditions. One can easily visualize the usefulness of this model in planning spray operations and in preparation of environmental assessments. The model also is a tool for examining the affects of a single parameter on spray coverage and drift. A FS publication by Rafferty (1984) provides graphic illustration (Figures 4 and 5) of 2,4-D drift relative to spray release height.

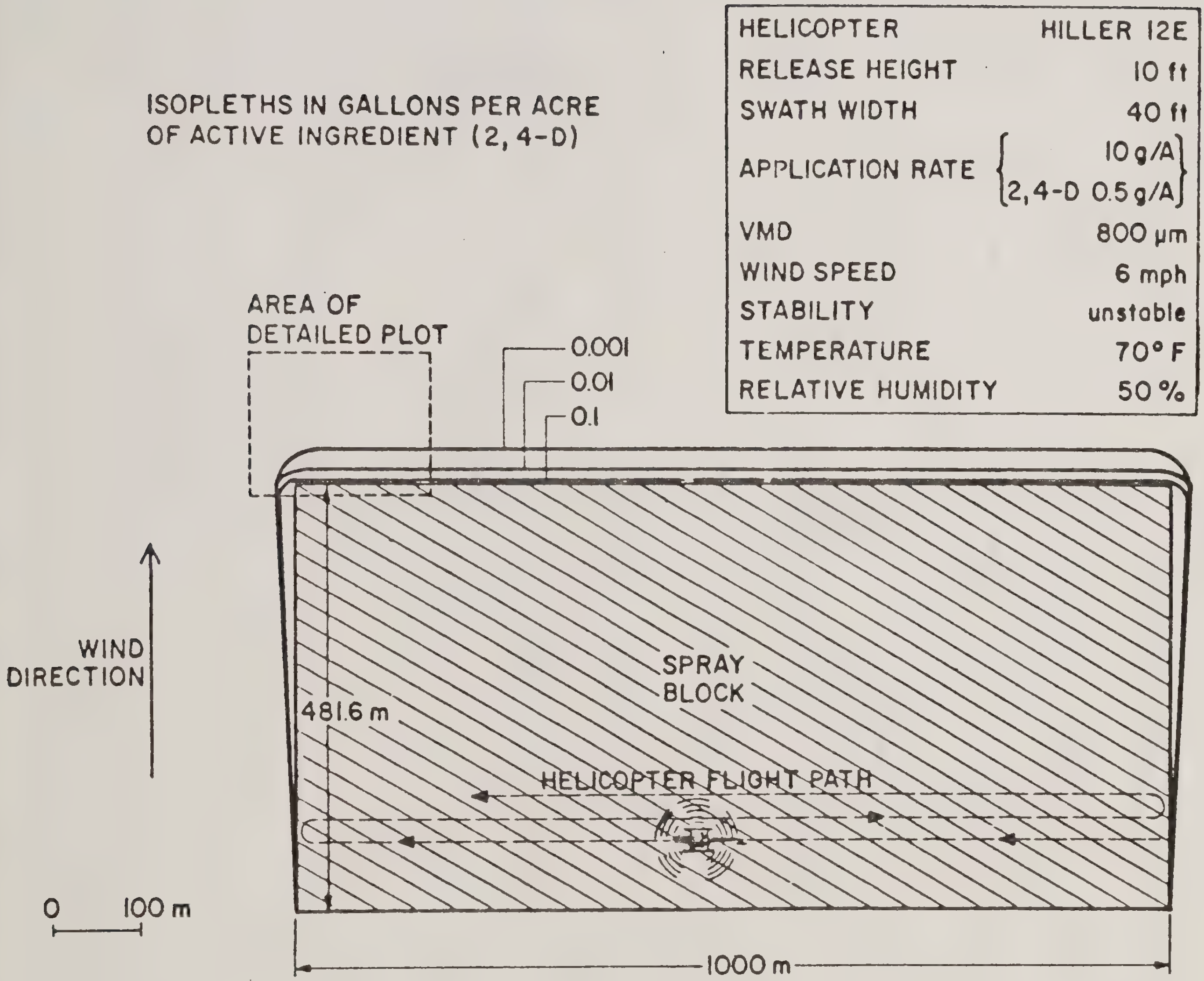

Figure 4. Prediction of drift for a release height of 10 ft. and a wind speed of 6 mph. (From Rafferty 1984).

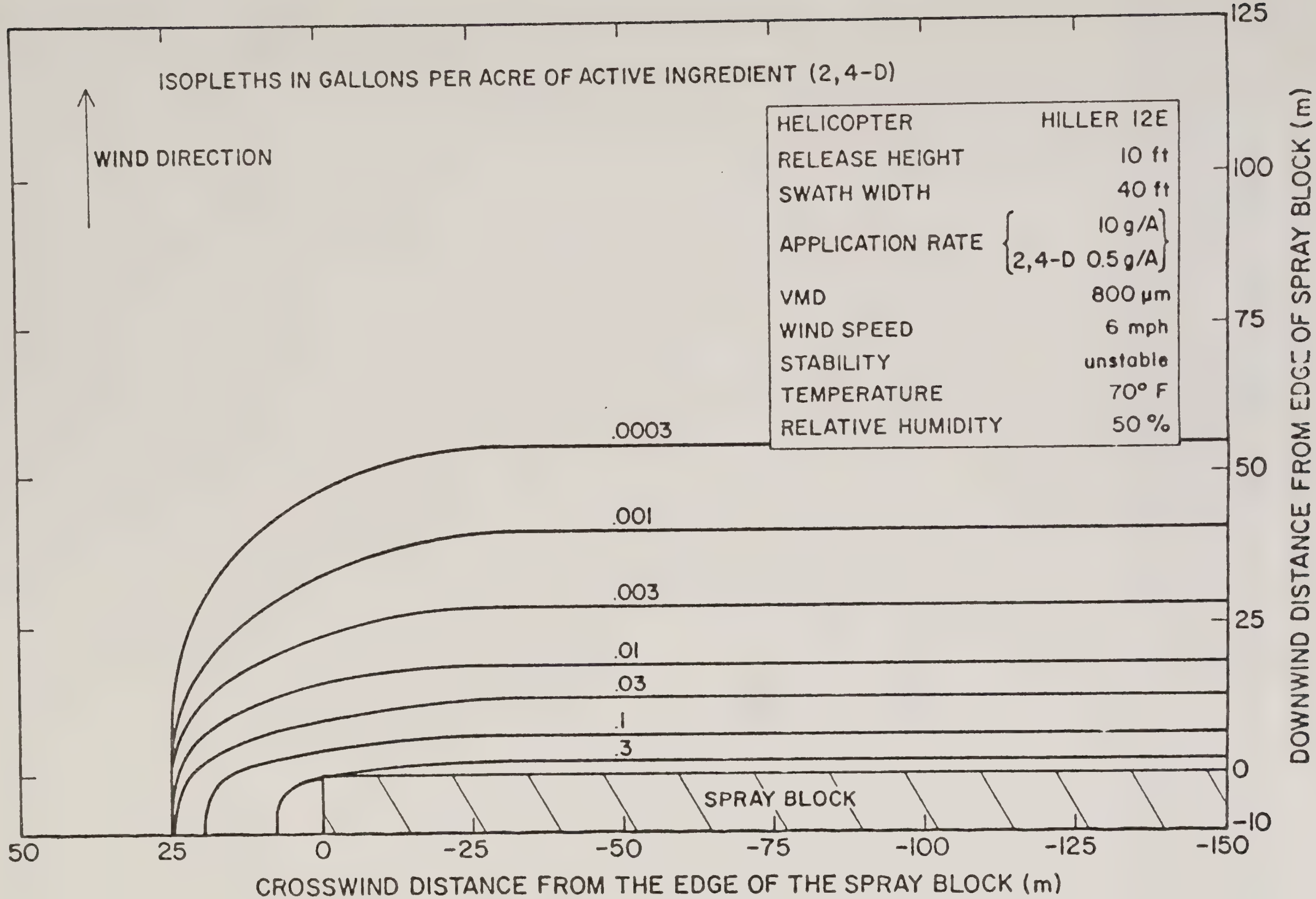

Figure 5. Detailed prediction of drift for a release height of 10 ft. and a wind speed of 6 mph. (From Rafferty 1984).

CONCLUSION

This paper has discussed the importance of drop size as it relates to covering the target area with herbicides and to controlling drift. Although we lack information on how to produce the optimum drop size range there are procedures that will contribute to improved applications. The state of the art provides us a capability to apply herbicides safely, efficaciously, and efficiently. It is up to you to seek and to use this existing information.

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